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Massive stars in sub-parsec rings around galactic centers.

Sergei Nayakshin

[1] *Dept. of Physics & Astronomy, University of Leicester, Leicester, LE1 7RH, UK*

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ABSTRACT

We consider the structure of self-gravitating marginally stable accretion disks in galactic centers in which a small fraction of the disk mass has been converted into proto-stars. We find that proto-stars accrete gaseous disk matter at prodigious rates. Mainly due to the stellar accretion luminosity, the disk heats up and geometrically thickens, shutting off further disk fragmentation. The existing proto-stars however continue to gain mass by gas accretion. As a results, the initial mass function for disk-born stars at distances $R \sim 0.03 - 3$ parsec from the super-massive black hole should be top-heavy. The effect is most pronounced at around $R \sim 0.1$ parsec. We suggest that this result explains observations of rings of young massive stars in our Galaxy and in M31, and predict that more of such rings will be discovered.

Key words: Galaxy: centre – accretion: accretion discs – galaxies: active – stars: formation

1 INTRODUCTION

Accretion disks around super-massive black holes (SMBHs) have been predicted to be gravitationally unstable at large radii where they become too cool to resist self-gravity and can collapse to form stars or planets (Paczyński, 1978; Kolykhalov & Sunyaev, 1980; Lin & Pringle, 1987; Collin & Zahn, 1999; Gammie, 2001; Goodman, 2003). There is now observational evidence that the two rings of young massive stars of size ~ 0.1 parsec in the centre of our Galaxy were formed in situ (Nayakshin & Sunyaev, 2005; Paumard et al., 2005), confirming the theoretical predictions. In our neighbouring Andromeda Galaxy (M31), Bender et al. (2005) recently discovered a population of hot blue stars in a disk or ring of similar size, i.e. with radius of ~ 0.15 parsec. The significance of this discovery is that SMBH in M31 is determined to be as massive as $M_{\rm BH} \approx 1.4 \times 10^8\,{\rm M}_{\odot}$, or about 40 times more massive than the SMBH in the Milky Way. This fact alone rules out (Eliot Quataert, private communication) the other plausible mechanism of forming stellar disks around SMBHs, e.g. the massive cluster migration scenario (e.g., Gerhard, 2001), because the shear presented by the M31 black hole is much stronger than it is at same distance from Sgr A*, and its hard to see how a realistic star cluster would be able to survive that (Gürkan & Rasio, 2005).

In this paper we shall attempt to understand what happens with the gaseous accretion disk around a SMBH when the disk crosses the boundary of the marginal stability to self-gravitation (Toomre, 1964) and forms first stars. We find that in a range of distances from SMBH, interestingly centered at $R \sim 0.1$ parsec, creation of first low-mass proto-stars should lead to very rapid accretion on these stars. The respective accretion luminosity greatly exceeds the disk radiative cooling, thus heating and puffing the disk up. The new thermal equilibrium reached is that of a disk stable to self-gravity where further disk *fragmentation* is shut off. Star formation is however continued via accretion onto the existing proto-stars, which then grow to large masses. We therefore predict that stellar disks around SMBHs should generically posses top-heavy IMF, as seems to be observed in Sgr A* (Nayakshin & Sunyaev, 2005; Nayakshin et al., 2005). In the discussion section we note three main differences between star formation process in a "normal" galactic environment and that in an accretion disk near a SMBH.

2 PRE-COLLAPSE ACCRETION DISK

In this section we determine the structure of the marginally stable accretion disk, $Q \approx 1$, i.e. the disk structure just before first gravitationally bound objects form. We envisage a situation in which the disk of a finite radius has been created by a "mass deposition event" on a time scale much shorter than the disk viscous time, but much longer than the local dynamical time, $1/\Omega$ (see below). Such an event could be a collision of two large gas clouds al larger distances from the SMBH, which cancelled most of the angular momentum of the gas, or cooling of a large quantity of hot gas that already had a specific angular momentum much smaller than that

* E-mail: `Sergei.Nayakshin` *at* `astro.le.ac.uk`

of the Galaxy (hot gas can be supported by its pressure in addition to rotation). In these conditions, it is reasonable to expect that the disk will settle into a local thermal equilibrium, in which the gas is heated via turbulence generated by self-gravitation (Gammie, 2001) and is cooled by radiation. The magnitude of viscosity α-parameter, and the disk cooling time, $t_{\rm cool}$, are then coupled by (Gammie, 2001; Levin, 2003; Rice et al., 2005):

$$t_{\rm cool} = \frac{4}{9}\,\frac{1}{\gamma(\gamma-1)\alpha\Omega} \tag{1}$$

where γ is the adiabatic index of gas. As we shall see below, for the parameters of interest, the evolution of the disk after star formation is turned on proceeds on a time scale again shorter than the local viscous time. Therefore, below we assume that the disk is in the hydrostatic and thermal equilibrium, but not in a steady accretion state, when the accretion rate $\dot{M}(R) = $ const. We now estimate the conditions in the disk (as a function of radius R) when it reaches surface density large enough to suffer local gravitational collapse. Star formation is a local process in this approach, and different rings in the disk could become gravitationally unstable at different times.

The appropriate accretion disk equations for $Q \sim 1$ have been discussed by many authors (see references in the Introduction). The hydrostatic balance condition yields

$$c_s^2 \equiv \frac{P}{\rho} = H^2\Omega^2\;, \tag{2}$$

where c_s is the isothermal sound speed, P and ρ are the total pressure and gas density, H is the disk scale height and $\Omega^2 = (GM_{\rm BH}/R^3 + \sigma_v^2/R^2)$ is the Keplerian angular frequency at radius R from the black hole. σ_v here is the stellar velocity dispersion just outside the SMBH radius of influence, i.e. where the total stellar mass becomes larger than $M_{\rm BH}$. Using equation 2, the disk midplane density is determined by inversion of the definition of Toomre (1964) Q-parameter:

$$\rho = \frac{\Omega^2}{\sqrt{2}\pi G Q}\;. \tag{3}$$

To solve for temperature of the disk, we should specify heating and cooling rates per unit area of the disk. The former is coupled to the rate of the mass transfer through the disk, $\dot{M}$:

$$Q_{\rm d}^+ = \frac{3\Omega^2\dot{M}}{8\pi}\;. \tag{4}$$

The accretion rate is given by

$$\dot{M} = 3\pi\nu\Sigma\;, \tag{5}$$

where $\Sigma = 2H\rho$ is the disk surface density. The kinematic viscosity ν in terms of the Shakura & Sunyaev (1973) prescription is $\nu = \alpha c_s H$. Marginally stable self-gravitating disks are believed to have $\alpha \sim 1$ (Lin & Pringle, 1987; Gammie, 2001; Rice et al., 2005) generated by spiral density waves.

The cooling rate of the disk (per side per unit surface area) is given by

$$F_{rad} = \frac{3}{8}\,\frac{\sigma T^4}{(\tau + 2/3\tau)}\;, \tag{6}$$

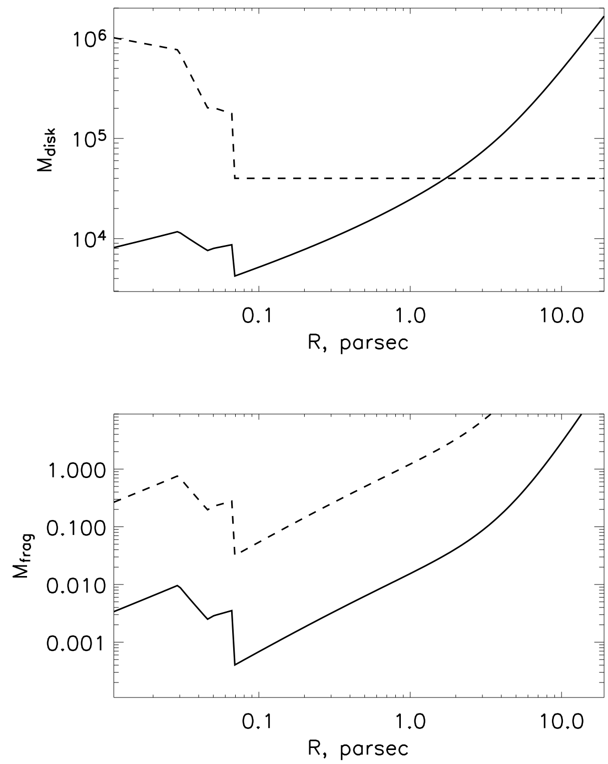

Figure 1. Disk mass (solid curve), $M_d = \pi\Sigma R^2$, and midplane temperature (dashed) as a function of distance from the SMBH are shown in the upper panel. The SMBH mass is that of Sgr A*. The lower panel shows two estimates of the mass of the first fragments forming in the disk. The realistic value of the fragments mass is likely to be in between these two curves.

where $\tau = \kappa\Sigma/2$ is the optical depth of the disk. This expression allows one to switch smoothly from the optically thick $\tau \gg 1$ to the optically thin $\tau \ll 1$ radiative cooling limits. We approximate the opacity coefficient κ following Table 3 in the Appendix of Bell & Lin (1994). For the problem at hand, it is just the first four entries in the Table are important as disk solutions with $T \gtrsim 2000$ K are thermally unstable(see also Appendix B in Thompson et al., 2005) since opacity rises as quickly as $\kappa \propto T^{10}$ in that region. This rather simple approximation to the opacities is justified for the order of magnitude parameter study that we intend to perform here. In addition, we set a minimum temperature of $T = 40$ K for our solutions. Even without any gas accretion, realistic gas disks near galactic centres will be heated by external stellar radiation to effective temperatures of this order or slightly larger. The main conclusions of this paper do not sensitively depend on the exact value of the minimum temperature or exact opacity law.

2.1 Masses of first stars in the disk

The upper panel of Figure 1 shows the resulting disk "mass" defined as $M_d = \pi\Sigma R^2$ and the midplane temperature (multiplied by 10^3). The lower panel of the Figure shows two estimates of mass of the first fragments in the disk. Different authors estimate the volumes of the first unstable fragments

slightly differently, but the reasonable range seems to be from H^3 to $2H \times (2\pi H)^2$. The two curves in the lower panel of Figure 1 should then encompass the reasonable outcomes, from $M_{\rm frag} = \rho H^3$ to $M_{\rm frag} = \rho 8\pi^2 H^3$. From the Figure, the fragment mass is, in the observationally interesting range of radii, i.e. $R \sim 0.1 - 1$ pc, $M_{\rm frag} \lesssim$ M$_\odot$, and hence if disk were to rapidly and completely collapse into clumps of mass of this order, one would expect low-mass stars or even giant planets to dominate the mass spectrum of collapsed objects.

Numerical simulations with a constant cooling time show (e.g., Gammie, 2001) that if the disk cooling time is at the threshold for the fragmentation to take place, then the first gas clumps will grow very rapidly by inelastic collisions with other clumps, possibly until they reach the isolation mass $M_{\rm iso} \sim (\pi R^2 \Sigma)^{3/2}/M_{\rm BH}^{1/2}$ (Levin, 2003). If this is the case, then the main point of our paper – that stars born in an accretion disk near a SMBH are massive on average – is proven, because the isolation mass can be hundreds to as much as 10^4 Solar masses (Goodman & Tan, 2004). However we suspect that Gammie (2001) simulations yielded no further gravitational collapse of the gas clumps precisely because the cooling time were kept constant. As the clump density increases, the clump free-fall time decreases as $\propto \rho^{-1/2}$, and hence the clumps could not collapse as they could not cool rapidly enough. It is quite likely that had the cooling time *inside the clumps* were allowed to decrease as the clumps get hotter, the clumps would collapse before they agglomerate into larger ones.

3 EFFECTS OF FIRST STARS ON THE DISK

We shall now assume that gravitational instabilities in the $Q \approx 1$ disc resulted in the formation of first proto-stars. According to the discussion in §2.1, we conservatively assume that these proto-stars are low mass objects, and show that in certain conditions even a small admixture of these to the accretion disk may significantly affect its evolution.

3.1 Coupling between stellar and gas disks

As the stars are born out of the gas in a turbulent disc, we assume that the initial stellar velocities are the sum of the bulk circular Keplerian velocity v_K in the azimuthal direction and a random component with three dimensional dispersion magnitude $\sigma_0 \approx c_s$. This also implies that at least initially stellar disk height-scale, H_*, is roughly the same as that of the gas disk, H. Proto-stars would interact by direct collisions and N-body scatterings between themselves and also via dynamical friction with the gas. The rate for proto-stellar collisions, $1/t_{\rm coll}$, is the sum of two terms, the geometric cross-section of the colliding stars and the gravitational focusing term (e.g., see Binney & Tremaine, 1987). One can show that $1/t_{\rm coll}\Omega \simeq \max[\Sigma_* R_{\rm coll}^2/M_*, (\Sigma_*/\Sigma) R_{\rm coll}/H]$, from which it is obvious that collisions are unimportant as long as the collision radius, $R_{\rm coll} \sim 2R_{\rm proto}$ (the proto-star radius), is much smaller than the disk height scale. In all of the cases considered below this will be satisfied by few orders of magnitude, therefore we shall neglect direct collisions.

The N-body evolution of the system of stars immersed into a gas disk is described by (Nayakshin & Cuadra, 2005)

$$\frac{d\sigma}{dt} \sim 4\pi G^2 M_* \left[\frac{\rho_* \ln\Lambda_*}{\sigma^2} - \frac{\rho C_{\rm d} \sigma}{(c_{\rm s}^2 + \sigma^2)^{3/2}}\right] \tag{7}$$

where $\ln\Lambda* \sim$ few is the Coulomb logarithm for stellar collisions, $C_{\rm d} \sim$ few is the drag coefficient for star-gas interactions (Artymowicz, 1994), σ is one-dimensional velocity dispersion, and $\rho_* = \Sigma_*/2H_*$ is the stellar surface density. Therefore, as long as the gas density $\rho \gtrsim \rho_*$, stellar velocity dispersion cannot grow as it is damped by interactions with the gas too efficiently. Recalling that $\rho_* = \Sigma_*/2H_*$, we find that in this situation

$$\frac{\sigma}{c_s} \approx \frac{H_*}{H} \sim \left(\frac{\Sigma_*}{\Sigma}\right)^{1/4} < 1\ . \tag{8}$$

Thus, initially, when $\Sigma_* \ll \Sigma$, stars are embedded in the gaseous disk and form a disk geometrically thinner than that of the gas. However, if stellar surface density grows and approaches that of the gaseous component, then the stellar velocity dispersion will run away. The stars then form a geometrically thicker disk (numerical simulations, to be reported in a future paper, confirm these predictions). Galaxy disks apparently operate in this regime, with molecular gas having a much smaller scale height than stars.

3.2 Accretion onto proto-stars

Since the stars remain embedded in the disk, they will continue to gain mass via gas accretion. Such accretion has been previously considered by many authors (e.g., Lissauer, 1987; Bate et al., 2003; Goodman & Tan, 2004). We assume that the accretion rate is

$$\dot{M}_* = \min\left[\dot{M}_{\rm Bondi}, \dot{M}_{\rm Hill}, \dot{M}_{\rm Edd}\right]\ , \tag{9}$$

where the accretion rates in the brackets are the Bondi, the Hill and the Eddington limit, respectively (e.g. Nayakshin, 2005). The latter is calculated based on the Thomson opacity of free electrons instead of dust opacity because we assume that the cooler regions of accretion flow onto the star are shielded from the stellar radiation by the inner, hotter accretion flow (Krumholz et al., 2005): $\dot{M}_{\rm Edd} = 10^{-3} r_*$ M$_\odot$ year^{-1}, where $r_* = R_*/R_\odot$.

3.3 Heating of the disc by proto-stars

Presence of the stars will lead to additional disc heating via radiation and outflows, and N-body scattering. The energy liberation rate per surface area due to N-body interactions is given by

$$Q^+_{*N} \sim \Sigma_* \sigma \left(\frac{d\sigma}{dt}\right)_* \sim 4\pi G^2 M_* \Sigma_* \frac{\rho_* \ln\Lambda_*}{\sigma}\ , \tag{10}$$

where $(d\sigma/dt)_*$ stands for the first term only in equation 7. Internal disk heating with the α-parameter equal to unity is

$$Q^+_{\rm d} = \frac{9}{4}\Sigma c_s^2 \Omega\ . \tag{11}$$

Comparing the stellar N-body heating with that of the internal disk heating, we have

$$\frac{Q^+_{*N}}{Q^+_{\rm d}} \sim \left(\frac{\Sigma_*}{\Sigma}\right)^{3/2} \frac{M_*}{M_{\rm BH}} \left(\frac{R}{H}\right)^3 \tag{12}$$

We have assumed above that Toomre-parameter $Q \sim 1$ when the stars just appear in the disk, and that $\Omega^2 =$

$GM_{\rm BH}/R^3$, i.e. that we are within the SMBH sphere of influence. Considering this expression for typical numbers, one notices that N-body heating is never important for large black holes and disks with finite disk thickness, i.e. at distances of tens of parsec and further away, but it may become important for smaller SMBH such as Sgr A* and sub-parsec distances.

Radiative internal output of the stars is another source of disk heating. We shall use a very simple parameterisation for the internal stellar luminosity as a function of mass, $L_* \propto M_*^3$. To this radiative output we should also add the accretion luminosity:

$$L_{\rm acc} = \frac{GM\dot{M}_*}{R_*}\;. \tag{13}$$

The sum should not exceed the Eddington limit, $L_{\rm Edd} = 4\pi GM_* m_p c/\sigma_T \approx 10^{38} m_*$ erg s^{-1}, and hence our prescription is

$$L_* = \min\left[L_\odot \frac{M_*^3}{{\rm M_\odot}^3} + L_{\rm acc}, L_{\rm Edd}\right]\;, \tag{14}$$

where $L_{\rm Edd} = 4\pi GM_* m_p c/\sigma_T$ is the Eddington limit with Thomson opacity σ_T. The radiative disk heating per unit surface area is then

$$Q^+_{*\rm rad} = \frac{\Sigma_*}{M_*} L_*\;. \tag{15}$$

4 ANALYTICAL ESTIMATES

As equation 3 suggests, accretion disks on parsec scales are as dense as 10^{12} particles cm^{-3}, which is multiple orders of magnitude denser than the densest gas in molecular clouds far from galactic centers. Therefore it is not surprising that the first proto-stars will be accreting at super-Eddington rates, typically. The corresponding accretion luminosity heating (equation 15 with $L_* = L_{\rm Edd}$) is

$$Q^+_{*\rm rad} \sim 10^5\ \Sigma_* r_*\ {\rm erg\ s^{-1} cm^{-2}}\;. \tag{16}$$

At the same time, the disk intrinsic heating at $Q \approx 1$ is, from equation 11,

$$Q^+_{\rm d} \approx \Sigma\, T_2\, \frac{M_{\rm BH}}{3\times 10^6\,{\rm M_\odot}} \left[\frac{0.1{\rm pc}}{R}\right]^{3/2} {\rm erg\ s^{-1} cm^{-2}}\;, \tag{17}$$

where Σ and Σ_* are in units of g cm^{-2}, and T_2 is the disk temperature in units of 100 K. We see that even a very small admixture of proto-stars ($\Sigma_* \ll \Sigma$) accreting at Eddington accretion rates will result in stellar heating much exceeding the intrinsic one. Since the disk thermal equilibrium is established on time scales comparable to the disk dynamical time, the disk will heat up at a constant Σ until its radiative losses can balance the accretion luminosity. This will increase the disk sound speed and the Toomre (1964) Q-parameter *above unity.* Therefore, the accretion feedback will stop further fragmentation from happening. The stars embedded into the disk will however continue to gain mass at very high rates. This should lead to a top-heavy initial mass function for the stars.

Note that a similar conclusion has been already reached by Levin (2003) who considered rather later stages in the evolution of a more massive AGN disk, when the high mass stars were turned into stellar mass black holes. He pointed out that accretion onto these embedded black holes will likely heat the disk, driving the Toomre (1964) Q-parameter above unity for radii somewhat smaller than a parsec.

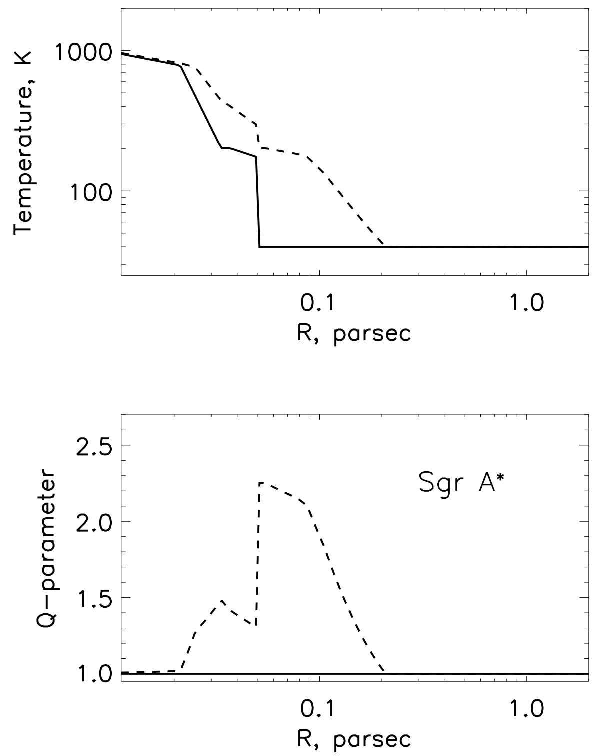

Figure 2. Temperature (upper panel) and Q-parameter (lower panel) versus radius in parsec for the marginally self-gravitating disk with (dashed) and without (solid) proto-stars embedded in the disks. The proto-stars have masses $M_* = 0.1\,{\rm M_\odot}$ and surface density $\Sigma_* = 0.001\Sigma$.

5 NUMERICAL RESULTS

We shall first consider the case of Sgr A* for which the mass of the SMBH is estimated to be $M_{\rm BH} \simeq 3.5\times 10^6\,{\rm M_\odot}$ (Schödel et al., 2002; Ghez et al., 2003). For the particular example, we shall accept that $\Sigma_* = 0.001\Sigma$ and that the initial masses of proto-stars are $M_* = 0.1\,{\rm M_\odot}$. The upper panel of Figure 2 shows the disk midplane temperature before the stars are introduced (solid) and after (dashed) versus radius R. Temperature of the gas increases for radii $0.03 \lesssim R \lesssim 0.2$ parsec. Toomre (1964) Q-parameter after the stars are introduced is plotted in the bottom panel of Figure 1. Q indeed becomes greater than unity in the same radial range, thus shutting off further gravitational collapse.

The radial range where the proto-stars shut off further fragmentation is rather insensitive to assumptions of our model. Figure 3 shows the Q-parameter after stars are introduced into the $Q = 1$ gaseous disk for Sgr A* case but with varying assumptions. In particular, the solid curve is the same as that in Figure 2, lower panel; the dotted one is calculated for the opacity coefficient κ multiplied arbitrarily by 3, whereas for the dashed one κ was divided by $\sqrt{T}$. These

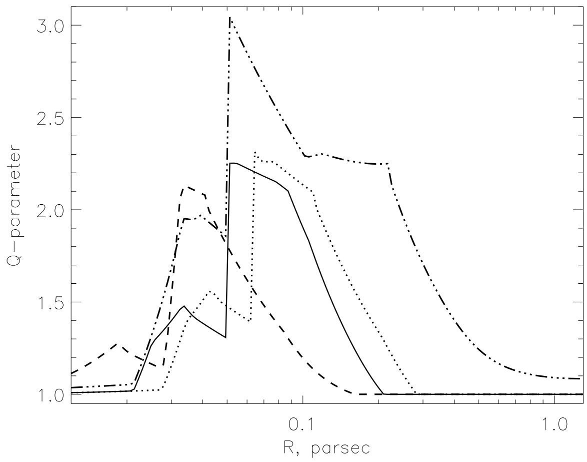

Figure 3. Toomre Q-parameter versus radius for the self-gravitating disk in which first stars were born. The solid line is the same as that in Figure 2, lower panel. The other curves are obtained by varying assumption of the model to test sensitivity of the results (see text).

arbitrary changes were introduced to estimate the degree to which the results are dependent on the (uncertain) opacity detail. Finally, the dot-dashed curve is calculated assumed the standard opacity but increasing the proto-stellar mass to $1\,M_\odot$ and stellar surface density Σ_* to 0.01, respectively. The stellar heating is then more pronounced and a larger area of the marginally stable disk can be affected.

We also consider the case of a more massive black hole, in particular we set $M_{\rm BH} = 1.4 \times 10^8\,M_\odot$, as thought to be the case for M31. Figure 4 shows the disk temperature structure (upper panel) before the collapse (dashed) and after the collapse. Note that these curves are almost identical to those for Sgr A* case except for a general shift to larger radii. This shift is about a factor of 3 only, which should not be surprising given that in the standard accretion disk theory (Shakura & Sunyaev, 1973) the midplane disk temperature is a very weak function of the central object mass.

6 DISCUSSION

In this semi-analytical paper, we studied the “first minutes” of an accretion disk around a super-massive black hole after the disk became unstable and formed first stars. We assumed that the disk accumulated its mass over time scales much longer than the local dynamical time, and is thus in a thermal equilibrium before the gravitational collapse. In this case, irrespectively of the typical mass of the first proto-stars, even a 0.1% admixture (by mass) of these significantly alters the thermal energy balance of the disk. The proto-stars accrete gas from the surrounding disk at very high (super-Eddington) rates at a range of disk radii. The accretion luminosity of these stars is sufficient to heat the disk up in that range of radii to the point where it becomes stable to self-gravity ($Q > 1$), which then shuts off further fragmentation of the disk. The proto-stars already present in the disc would however continue to gain mass at very high rates. Quite generally, then, an average star created in such

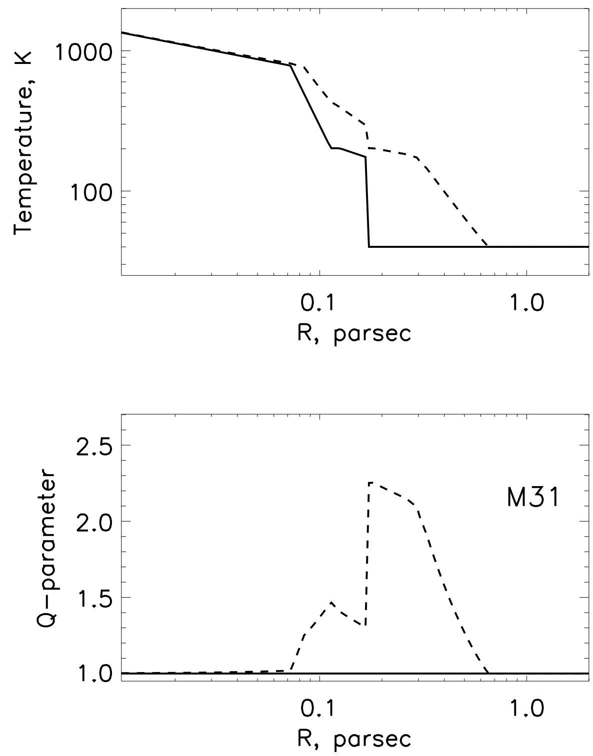

Figure 4. Same model as that used for Figure 1, except for a higher SMBH mass, $M_{\rm BH} = 1.4 \times 10^8\,M_\odot$. Note that, compared with Figure 1, the radial range where proto-stars succeed in heating the disk up has shifted to slightly larger radii.

a disk will be a massive one, in stark contrast to the typical galactic star formation event.

Significance of accretion feedback onto embedded *stellar mass black holes* for accretion disks near galactic centres was pointed out by Levin (2003). He noted that the accretion disks can be stabilised by the feedback out to radius of about one parsec, in good agreement with our results. Since the Eddington luminosity depends only on the disk opacity and the mass of the central object, it is then not really surprising that the feedback is effective for accretion onto stars as well.

The range of radial distances from the SMBH where this effect operates is a slow function of the SMBH mass, and is typically from a fraction of 0.1 parsec to a few parsec, with the peak of the effect taking place at $R \sim 0.1$ parsec. The reason why the feedback is only effective in a range of radii is that at large radii, i.e. tens of parsec, the gas density in the disk drops significantly so that accretion rates onto the proto-stars become much smaller than the respective Eddington-limited rates. At radii much smaller than ~ 0.1 parsec, the intrinsic disk heating (equation 17) becomes very large. A related point is that steady-state constant accretion rate disk models show that there is always the minimum radius where star formation becomes impossible as $Q > 1$ there (e.g. Goodman, 2003; Levin, 2003; Nayakshin & Cuadra, 2005). The value of the minimum distance where star formation should be expected is comparable to the minimum radius for which we predict favourable conditions for development of a top-heavy IMF.

We suggest that the uncommonly effective feedback from star formation on low-mass proto-stars may be relevant for the formation of rings of massive stars observed in the Galactic Centre and in the nucleus of M31. In particular, Nayakshin et al. (2005); Nayakshin & Sunyaev (2005) have shown from two completely independent lines of evidence that the IMF of stellar disks in the Galactic Centre must have been very top-heavy, with the mass of Solar-type stars accounting for no more than $\sim 50\%$ of the total, the remainder being in the $M \gtrsim 30\,\mathrm{M}_\odot$ stars. The insensitivity of our results to details of the model and the SMBH mass suggest that the IMF of stars born inside accretion disks near galactic centers may be generically top-heavy, which would have long-ranging consequences for the accretion theory in AGN.

6.1 Generality and shortcomings of this work

In this paper we concentrated on the growth of proto-stellar mass via accretion of gas. As discussed in §3, in certain conditions the mass of gas clumps before they collapse to form a star may be much higher than the Jeans mass. This would only increase the expected final mass of a typical star in the disk. The same is true for direct collisions of proto-stars, the other channel via which proto-stars may grow (see §3.1).

In addition, we have here limited the rate at which the proto-star would grow to the Eddington accretion rate onto a star. This is important if the rate at which the gas is captured in the sphere of influence of the proto-star, the Hill or the Bondi radius, whichever is smaller, exceeds the Eddington accretion rate. It is possible that in reality the excess gas settles into a rotationally supported "proto-stellar" disk from which further generations of stars may be born (Milosavljević & Loeb, 2004). It is not obviously clear whether this effect would increase the average mass of the stars or would rather decrease it. On the one hand, fragmentation of the proto-stellar disk may give rise to many low mass stars. On the other, though, these stars may be then driven into the central more massive star by the continuing gas accretion, as suggested by Bonnell & Bate (2005). In the latter case the central star may in fact grow faster than the Eddington accretion rate.

On the balance, we believe that the main conclusion of our work, e.g. the unusually high (perhaps dominant) fraction of the total mass going into creation of high mass stars as opposed to low mass stars, may be rather robust. One clear exception to this will be a very rapid (dynamical) gravitational collapse of a disc. For example, when a large quantity of gas (compared to the minimum needed for the disk to become self-gravitating, see Figure 1) cools off very rapidly and settles into a disc configuration, and the cooling time is shorter than dynamical time, the disc will break into self-gravitating low mass objects before it can establish thermal balance (e.g., Shlosman & Begelman, 1989).

We deliberately stayed away here from discussing the much more complicated question of the eventual disk evolution. The answer depends not only on the initial radial structure of the disk but also on how the disk is fed with gas after it crossed the self-gravity instability threshold. We shall investigate these issues in our future work (note that Thompson et al. 2005 recently developed a model for kilo-parsec scale star-forming disks in ultra-luminous galaxies).

6.2 Why different from "normal" star formation?

It is instructive to emphasise the differences in star formation rates near a SMBH and in a galaxy. Consider the relevant gravitational collapse time scales t_c. For accretion disks around the SMBH, this is $t_c \simeq 1/\Omega \approx$ 60 years $(R/0.04 \text{ parsec})^{3/2}$ $(M_{\rm BH}/3\times10^6\,\mathrm{M}_\odot)^{-1}$, which is shorter than the Eddington limit doubling time of $\sim$ a thousand years. Compare this time with the free-fall time for a molecular cloud of mass $10^3\,\mathrm{M}_\odot$ and size of 1 parsec: $t_{\rm ff} \sim 10^6$ years. Clearly, then, an average accretion rate in the galactic environment is orders of magnitude below the Eddington limit, and no significant radiation feedback should be expected from *low mass* proto-stars. The latter can then form in great numbers with little damage to the rest of the cloud, unlike in the case of a massive disk.

Another significant qualitative difference is that the escape temperatures, $T_{\rm esc} \sim GM\mu/kR$, are vastly different near a SMBH and inside a molecular cloud. For the former, it is typically in the range of $10^6 - 10^7$ K, whereas for the latter it is only $\sim$ few $\times 10^3$ K. Hence, while photo-ionizing feedback from massive stars may unbind most of the gas in a molecular cloud, stopping not only further fragmentation but also further accretional growth of proto-stars, in SMBH disks the effect is local (e.g., Milosavljević & Loeb, 2004). In particular, it simply increases the disk scale-height until the gravity of the SMBH (which increases as z/H for thin accretion disks, e.g., Shakura & Sunyaev, 1973) is strong enough to hold the gas in place. In other words, accretion or any other star formation feedback in a disk environment may be strong enough to prevent further disk fragmentation but not the growth of the existing proto-stars.

Third important difference is geometry. Most stars in a molecular cloud move on orbits different from those of the gas, as the latter is influenced by both gravity and pressure forces whereas stars obey only the gravity. Hence the gas and the stars may be separated out in space, terminating accretion onto the stars. In contrast, as is well known from the standard accretion theory (Shakura & Sunyaev, 1973), gas pressure forces are very small compared to the SMBH gravity for thin gas disks in galactic centers, and so both stars and gas follow essentially circular Keplerian orbits around the SMBH (Nayakshin & Cuadra, 2005). Therefore the stars are always not too far away from the gas and hence have a much better chance to gain more mass by accretion.

7 CONCLUSIONS

In this paper we have shown that the birth of even a small number (by mass fraction) of low-mass proto-stars inside a marginally stable accretion disk near a galactic center will unleash a very strong thermal feedback onto the gaseous disk. In a sub-parsec range of radii, the disk will be heated and thickened so that it becomes stable to further fragmentation. The feedback however is not strong enough to unbind the gas from the deep potential well of the SMBH. Therefore, while the feedback stops a further disk fragmentation, accretional growth of stars already present in the disk proceed. Quite generically, this scenario should lead to the average star created in the SMBH accretion disk being "obese" compared to its galactic cousins.

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